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1 **Monitoring recent lake level variations on the Tibetan Plateau using CryoSat-2**

2 **SARIn mode data**

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9 **Abstract**

10 Lakes on the Tibetan Plateau (TP) are of great interest due to their value as water resources but
11 also as an important indicator of climate change. However, in situ data in this region are
12 extremely scarce and only a few lakes have gauge measurements. Satellite altimetry has been
13 used successfully to monitor lake levels. In this study, Cryosat-2 SARIn mode data over the
14 period 2010 to 2015 are used to investigate recent lake level variations. The estimated water
15 levels of the 70 largest lakes ($> 100 \text{ km}^2$) on the TP show that 48 lakes reveal a rising trend
16 (avg. $0.28 \pm 0.06 \text{ m/yr}$) while the other 22 show a slightly decreasing trend (avg. -0.10 ± 0.04
17 m/yr). To compare with the change rates during 2003-2009, ICESat data which cover 42 of the
18 70 lakes are also used. When combining the data, the results show that during the period of
19 2003-2015, 28 lakes maintained a rising trend and the change rates are comparable. Lakes in
20 the northern part of the TP experienced pronounced rising (avg. $0.37 \pm 0.10 \text{ m/yr}$), while lakes
21 in southern part were steady or decreasing even in glaciated basins with high precipitation.

22 Factor analysis indicates that driving factors for lake change are variable due to high spatial
23 heterogeneity. However, autumn/winter temperature plays an important role in lake level
24 change. These results demonstrate that lakes on the TP are still rapidly changing under climate
25 change, especially in northern part of the TP, but the driving factors are variable and more
26 research is needed to understand the mechanisms behind observed changes.

27 **Keywords:** Lake Level; Tibetan Plateau; Altimetry; Cryosat-2; SARIn

28 **1. Introduction**

29 The Tibetan Plateau (TP), with an average elevation of more than 4000 m-amsl and an area
30 of approximately 2.5 million km², is China's largest and the world's highest highland. The TP
31 plays a significant role in the regional and global climate system due to its large area and high
32 altitude(Wu et al., 2007; Yanai and Li, 1994). It is important for Asian monsoon development
33 and water-energy cycles (Molnar et al., 2010). The TP has the largest ice mass outside the Arctic
34 and Antarctic regions. The snow and ice masses feed many large rivers which provide water to
35 more than 1.4 billion people (Immerzeel et al., 2010). The TP is characterized by thousands of
36 lakes, which cover an area of 41831 km² (Wan et al., 2014). Therefore, the TP is also called the
37 "Asian water tower" (Lu et al., 2005). Besides their value as water resources, lakes are critical
38 landscape units which play an important role in the land surface energy cycle and thus impact
39 the regional climate and water circulation. However, most of the lakes have experienced great
40 changes during the past three decades and are still changing rapidly due to climate change. The
41 investigation of Wan et al. (Wan et al., 2014) indicated that about 30 new lakes appeared and 5
42 existing lakes have dried up and vanished in the period of 1975-2006. In addition, most of the

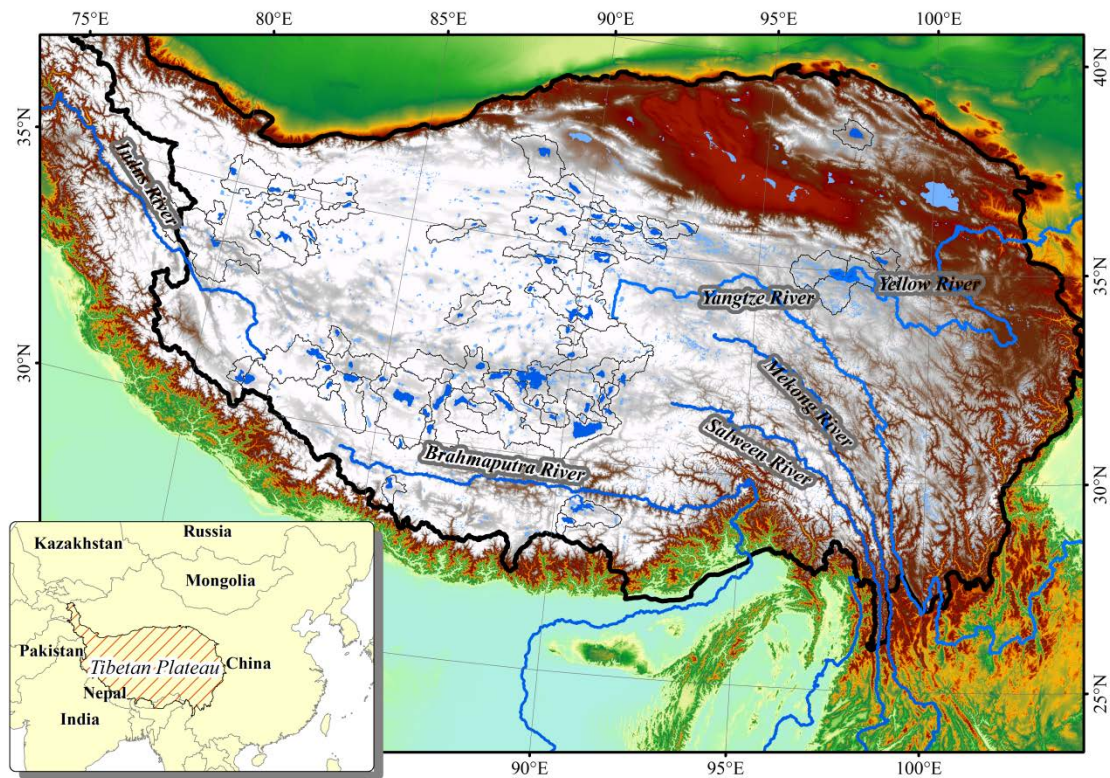
43 largest 13 lakes (> 500 km²) experienced drastic changes. For instance, Siling Co has expanded
44 by 600 km² accounting for about 26% of total area since 1976 (Zhou et al., 2015), while the
45 size of Qinghai Lake first decreased by 231 km² and then expanded by 134 km² during 1973-
46 2013 (Shen et al., 2013).

47 Satellite radar altimetry has been a successful technique and widely used to monitor lake
48 level variations (Berry et al., 2005; Birkett, 1995; Crétaux et al., 2016; Crétaux and Birkett,
49 2006; Gao et al., 2013; Kleinherenbrink et al., 2015; Liao et al., 2014; Song et al., 2014, 2015a,
50 2015b, 2015c). It has become a very important alternative data source to in situ observations,
51 especially in remote areas where in situ data are not available, e.g. the TP. Among several
52 conventional radar satellite missions (Topex/Poseidon, Jason, ERS, ENVISAT, etc.), the new
53 generation of radar altimetry, CryoSat-2 has some advantages. The CryoSat-2 mission,
54 launched in April 2010, has been operational for 6 years in April 2016. Cryosat-2 features a
55 delay/Doppler technology. Its primary instrument, the Ku-Band Synthetic Aperture
56 Interferometric Radar Altimeter (SIRAL), has three measurement modes: low resolution mode
57 (LRM), synthetic aperture radar mode (SAR) and SAR interference mode (SARIn).
58 Additionally, CryoSat-2 has a repeat period of 369 days and an inclination of 92 degrees, thus
59 it covers a larger area than previous missions. Meanwhile, it has a subcycle of 30 days, that is
60 to say, the density of ground tracks is high, thus many lakes are visited (European Space Agency
61 and Mullar Space Science Laboratory, 2012; Kleinherenbrink et al., 2014; Nielsen et al., 2015).

62 The TP is a crucial testing ground for application of altimetry on inland water because of
63 its numerous lakes (Fig. 1) and the lack of gauge-based observations. Ice, Cloud, and land
64 Elevation / Geoscience Laser Altimeter System (ICESat/GLAS) demonstrated its value in

65 monitoring lake level change (Phan et al., 2012; Song et al., 2013; Zhang et al., 2011). In the
66 past few years, a growing number of studies have used ICESat/GLAS to retrieve lake level time
67 series (Li et al., 2014; O’Loughlin et al., 2016; Phan et al., 2012; Wang et al., 2013; Zhang et
68 al., 2011). Nevertheless, the application of CryoSat-2 in hydrology community is still in its
69 infancy. Kleinherenbrink et al. (2015) first presented the application of CryoSat-2 SARIn mode
70 data over the period February 2012 to January 2014 to monitor lakes on the TP. However, more
71 research is needed to explore the full potential of Cryosat-2 in monitoring of inland water level.

72 In this paper, we investigate water level change of large lakes ($> 100 \text{ km}^2$) on the TP using
73 CryoSat-2 SARIn mode data of 2010-2015. We apply the Narrow Primary Peak Threshold
74 (NPPT) retracker (Jain et al., 2015), which has proven to provide valid results for inland water
75 applications (Nielsen et al., 2015; Villadsen et al., 2016). In terms of height precision, the NPPT
76 retracker is seen to outperform the ESA L2 data (Jain et al., 2015), but for studies of lake level
77 change there is only in-significant difference depending on the choice of NPPT versus L2
78 retracker. Finally we estimate the along-track mean water level for each pass using a robust
79 method (Nielsen et al., 2015). Lake level changes are compared during two periods of 2003-
80 2009 and 2010-2015, and the potential causes of lake change are investigated.



81
 82 Figure 1: Topographic map of the Tibetan Plateau and distribution of large rivers and
 83 lakes (studied lakes are shown in blue)

84 **2. Data and methods**

85 *2.1. Water mask*

86 Landsat 8 OLI and Landsat 7 ETM+ images were downloaded via the United States
 87 Geological Survey (USGS) EarthExplorer (<http://earthexplorer.usgs.gov/>) to delineate the lake
 88 masks. The acquisition dates of all images are between May to December of 2014 to get high
 89 quality images over lakes. In total, 34 scenes of Landsat 8 OLI and 18 of Landsat ETM+ were
 90 used to derive the lake mask. Considering the efficiency and quality of different methods, a
 91 threshold-based approach was used combined with visual examination. The thresholds of DN
 92 35-40 and 5000-5600 was used to extract the lake body with band 5 (Landsat 7) and band 6
 93 (Landsat 8) depending on the date of image acquisition.

94 2.2. *CryoSat-2*

95 2.2.1. Lake level estimation

96 The ESA level 1b baseline B data product in SARIn mode was used as input. The
97 waveforms were retracked using the Narrow Primary Peak Threshold (NPPT retracker (Jain et
98 al., 2015)). The range R is computed as:

99
$$R = R_{wd} + R_r + R_{gc}, \quad (1)$$

100 where R_{wd} is the window delay; R_r is the retracker correction and R_{gc} is geophysical corrections
101 including ionosphere, wet and dry troposphere, solid earth tide, ocean loading tide, and pole
102 tide. Both R_{wd} and R_{gc} are available in the L1b data product.

103 In SARIn mode, the SIRAL altimeter, employs both antennas, which makes it possible
104 to detect the origin of the echo. Hence, it is possible to estimate the range correction, which
105 occurs, when the reflector is not at the nadir position. The range correction is here estimated
106 according to Armitage and Davidson (2014). The lakes on the TP are completely or partly
107 frozen during parts of the year, which might influence the ranges (Sørensen et al., 2011).

108 Finally, the surface elevations H with respect to the Earth Gravitational Model of 2008
109 geoid (EGM2008) are obtained using the following expression:

110
$$H = h - R - N, \quad (2)$$

111 where h is the satellite altitude and N is the geoid height with respect to the ellipsoid. Since
112 Cryosat-2 is overflying the lakes at different positions potential residual geoid errors might be
113 present in the constructed time series.

114 2.2.2. Times series construction

115 After extraction by lake masks, the water level time series for 70 lakes were estimated
116 using the “R” package tsHydro (<https://github.com/cavios/tshydro>). The core of tsHydro is a
117 state-space model, where the process model is described by a simple random walk and the
118 observation model is described by the true water level and an error term. The error structure is
119 modelled by a mixture between Normal and Cauchy distributions. The distribution has heavier
120 tails compared to a pure Normal distribution, which makes the model robust against erroneous
121 observations. The model is detailed in Nielsen et al. (2015). Figure 2 illustrates the water level
122 estimation processes.

123 2.3. ICESat

124 The ICESat was a laser altimeter mission that operated during 2003-2009. It was used to
125 compare the lake level variations from Cryosat-2. The ICESat data were obtained from IWSH
126 (<http://data.bris.ac.uk/data/dataset/15hbqgewcrti51hmzp69bi4gky>) (O’Loughlin et al., 2016),
127 which already includes geodetic and atmospheric corrections, and outlier removal. Before
128 extracting data by our mask, the height is converted from EGM96 to EGM2008 to be consistent
129 with Cryosat-2 data.

130 2.4. Trend estimation and storage change calculation

131 To estimate the overall change trend of lake levels, a linear model is used. The trend (or
132 rate of lake level change) is estimated by fitting the following equation to the observations using
133 a least squares method:

$$134 \quad y = \beta_0 + \beta_1 t \quad (3)$$

135 where y is the lake level time series; β_0 and β_1 are the parameters to be estimated, and t is the
 136 time (decimal year). β_1 is the trend in units of meter per year.

137 The formula for calculating the storage change is applied by assuming that the
 138 volume is a circular cone (Taube, 2000):

$$139 \quad V = \frac{1}{3}(H_2 - H_1)(A_1 + A_2 + \sqrt{A_1 \times A_2})/1000 \quad (4)$$

140 where V is the storage change (10^9 m^3); H_1 and H_2 are the level (m) at the start and
 141 end of a period, and A_1 and A_2 are corresponding lake areas (km^2).

142 2.5. Regression analysis

143 Factor analysis is performed to find the underlying relationship between lake level change
 144 and different factors. Both weighted linear regression and multiple linear regression are used in
 145 this context.

146 Instead of minimizing the sum of squared residuals (SSR),

$$147 \quad SSR = \sum_{i=1}^n [\beta_{1i} - (\alpha_0 + \alpha_1 x_i)]^2 \quad (5)$$

148 we minimize a weighted sum of squared residuals (WSSR),

$$149 \quad WSSR = \sum_{i=1}^n w_i [\beta_{1i} - (\alpha_0 + \alpha_1 x_i)]^2 \quad (6)$$

150 and we use weight w ,

$$151 \quad w = \frac{1}{\sigma^2} \quad (7)$$

152 where x is any factor (e.g. latitude, temperature/precipitation change rate, etc.); α_0 and α_1 are
 153 the parameters to be estimated; β_1 and σ are trend and standard error of the trend, respectively,
 154 obtained from fitting Eq. (3), and n is the number of lakes.

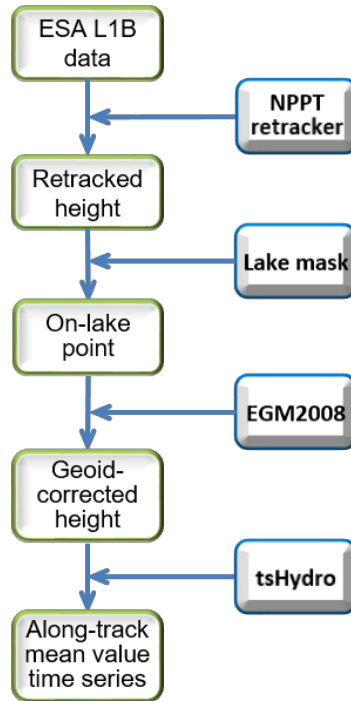
155 2.6. Auxiliary data

156 The HydroBASINS product (<http://www.hydrosheds.org/page/hydrobasins>) was used as
157 reference data to delineate lake basins. To ensure the accuracy of each lake basin, the
158 watersheds from the HydroBASINS dataset were visually checked with SRTM DEM. Some
159 debris polygons were merged and some lake basins embedded in bigger basins were delineated
160 separately. All basin-averaged parameters, i.e. temperature, precipitation, supply coefficient
161 (basin area minus lake area, divided by lake area), glacier ratio (glacier area divided by the
162 difference between basin area and lake area), snow/rain ratio, basin elevation are calculated
163 using this basin dataset.

164 Monthly precipitation and temperature data for 1985-2014 are obtained from the China
165 Meteorological Data Sharing Service System (<http://data.cma.cn/>), and also 30 year-averaged
166 daily precipitation and temperature data, which is used to calculate snow/rain ratio depending
167 on the corresponding temperature. The gridded dataset at $0.5^\circ \times 0.5^\circ$ spatial resolution is
168 produced by the National Meteorological Information Center (NMIC) of the China
169 Meteorological Administration (CMA), by interpolating observations of 2472 stations
170 (including national Reference Climate Network stations, Basic Meteorological Network
171 stations and national Ordinary Meteorological Network stations) using the thin plate spline
172 method. We calculated the climate normals and change rate for precipitation and mean,
173 minimum and maximum temperatures. The Randolph Glacier Inventory 5.0
174 (http://www.glims.org/RGI/rgi50_dl.html) is used to calculate the glacier ratio.

175 Lake area of 2010 is obtained from Third Pole Environment database

176 (<http://www.tpedatabase.cn/>). Combined with lake area of 2014 and lake level data, storage
177 change is calculated using Eq. (4).

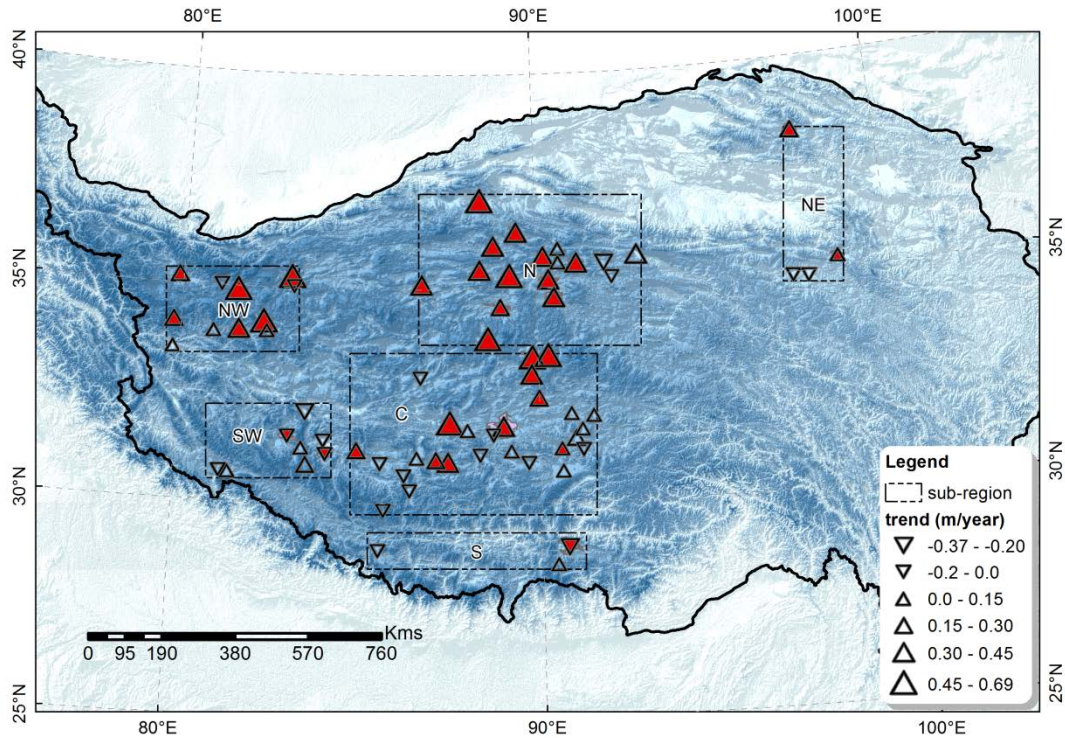


178
179 Figure 2: Flowchart of water level estimation

180 3. Results

181 3.1. Overview of lake level change

182 In total, 70 lakes having at least 10 passes are considered in this study and the average
183 length of time series is 34 (Table 1). Our results of lake level change rate are depicted in Figure
184 2. It is clear that, most lakes show a significant increasing trend. To be specific, 48 lakes reveal
185 rising trend (30 are significant at 95% Confidence Level (CL)) with mean rate of 0.28 m/yr
186 while the other 22 show falling trend (3 are significant at 95% CL) with mean rate of -0.10 m/yr.
187 Lakes are grouped into different sub-regions according to their geography, topography and
188 climatic characteristics (Table 2 & Fig. 3).

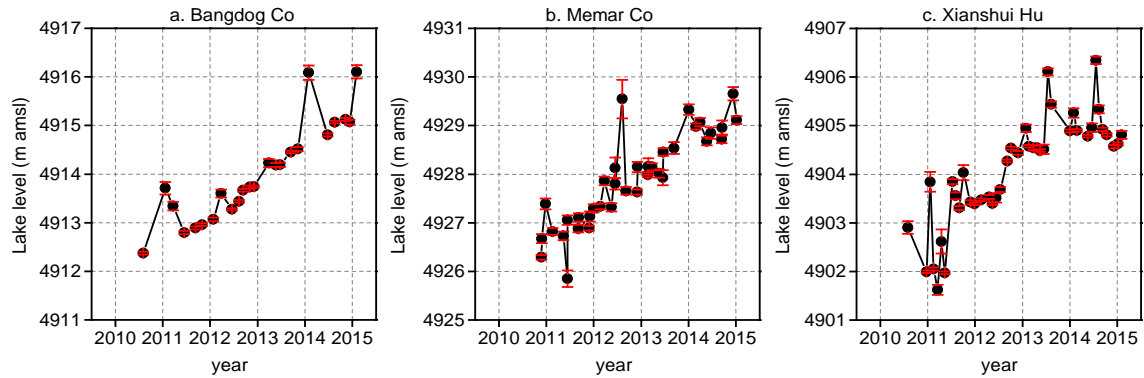


189

190 Figure 3: Spatial distributions of lake level changing trends. Upward/downward
 191 triangles represent positive/negative trends. Solid-red triangles indicate significant
 192 trends at the 95% confidence level

193

194 Sub-region NW: In the northwestern part of the TP, characterized by higher elevation (avg.
 195 5232 m), cold and arid climate, dominated by the westerly (Yao et al., 2013). In this region,
 196 glacier and snow cover are widely distributed. Most lakes are fed by glacier- and snow-melt
 197 water (Wang and Dou, 1998). Seven of nine lakes show a rising trend. Bangdag Co, Memar Co
 198 and Xianshui Hu are the top three with rising rate in the order of 0.7 m/yr (Fig. 4). Only Gozha
 199 Co and Pelrap Tso declined slightly (- 0.09 m/yr).

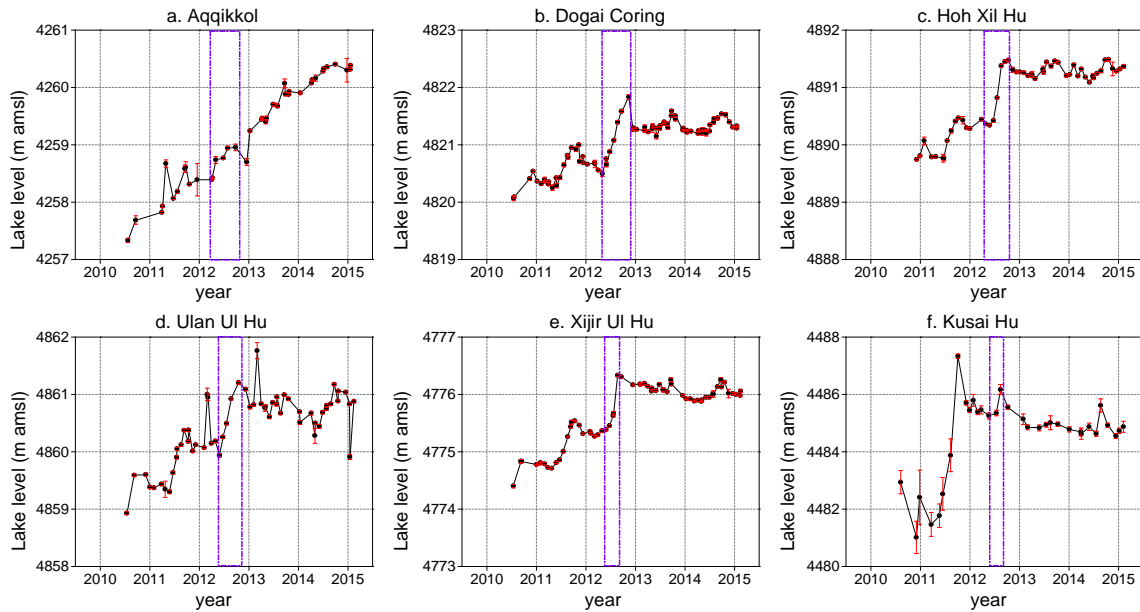


200

201 Figure 4: Time series of Bangdog Co, Memar Co and Xianshui Hu water level
 202 variations

203

204 Sub-region N: This sub-region lies in the Hoh Xil region, which is the so-called “No-man’s
 205 land”, known for its harsh environment, i.e., low temperature, strong wind and low oxygen
 206 content. In this region, lakes are distributed densely and most of them are endorheic lakes. As
 207 listed in Table 2, 88% of the lakes were expanding at an average rate of 0.374 m/yr. Aqqikkol
 208 lake level increased at the largest rate of 0.681 m/yr and is now the second largest lake by area
 209 in this sub-region. The largest lake, Ulan Ul lake, also exhibited a significant trend of 0.329
 210 m/yr. The increase in water storage in this sub-region is substantial considering their large areas
 211 (avg. 300 km²) and rising rates. It should be noted that most of the lakes in this sub-region show
 212 a period of rapid level change (0.4 - 1.1 m) during March to October 2012, and most of these
 213 lakes show a steady state in recent two years (Fig. 5).



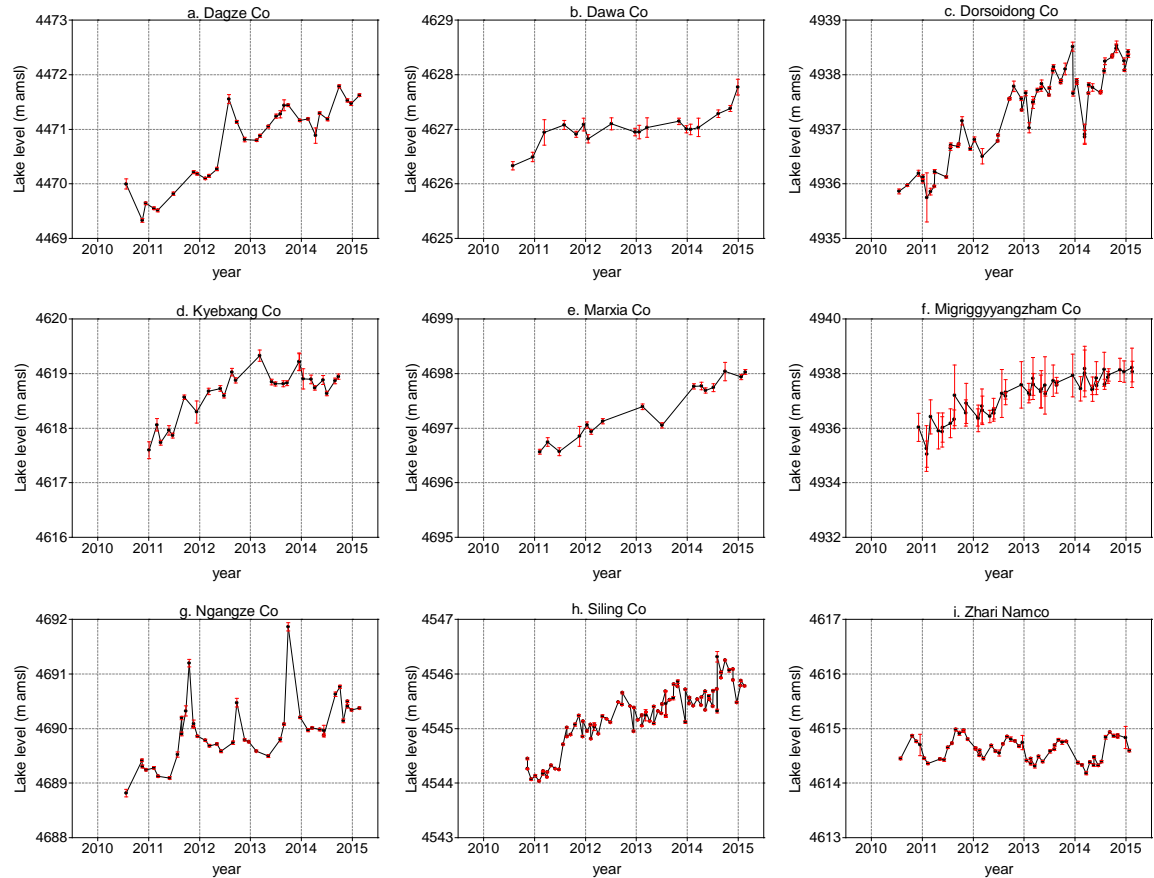
214

215 Figure 5: Time series of six lakes water level in sub-region N with pronounced sharp
 216 increase in 2012

217

218 Sub-region SW: In this region, all lakes were relatively steady. Even though decreasing
 219 trends are dominant, the change rates are low (< 0.164 m/yr).

220 Sub-region C: 38.5% of the lakes investigated are located in this region. Lake level changes
 221 in this region are heterogeneous. However, increasing trends are dominating (Fig. 6). The
 222 average increasing and declining rates are 0.22 and -0.072 m/yr, respectively. Dorsoidong Co
 223 and Migriggyangzham Co experienced the fastest rising. The level increase exceeds 2 m for
 224 both lakes (Fig. 6). Siling Co shows an abrupt rising in 2011 and is now larger than Nam Co,
 225 being the second largest salt lake in China and it is still rising at the rate of 0.374 m/yr (Fig. 6).
 226 Nine lakes are slightly decreasing, such as Zhari Namco (Fig. 6).



227

228 Figure 6: Time series of water level from nine lakes in sub-region C

229 Sub-region S: This region lies in Yarlung Tsangpo (Brahmaputra) river basin. Peiku Co
 230 and Yamdrok Lake show a clear decreasing trend, while Puma Yumco has a slight rising trend.

231 Yamdrok, the largest in southern TP, had been decreasing at -0.366 m/yr.

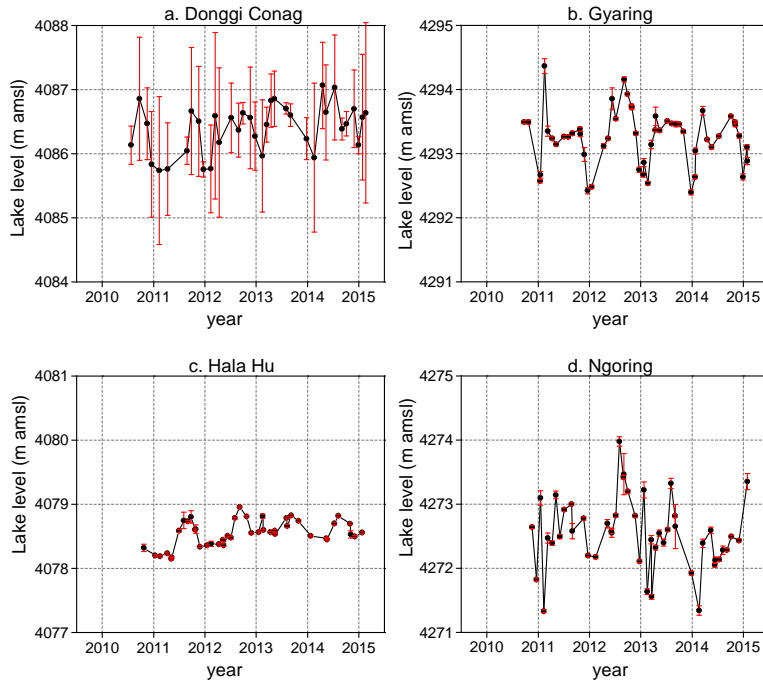
232 Sub-region NE: This is the three-rivers source region and Qaidam Basin in the Qinghai province.

233 In this region, lakes were almost steady (Fig. 7). Sister lakes Ngoring and Gyaring show a slight

234 decreasing trend, at rates of -0.06 and -0.02 m/yr. Both Ngoring and Gyaring have a large

235 fluctuation in 2012. Comparatively, Hala Hu and Doggi Conag were rising at 0.16 and 0.11

236 m/yr.



237

238 Figure 7: Lake level changes of Doggi Conag, Gyaring, Hala Hu and Ngoring

239 In summary, lake rising is the dominant trend despite some lakes showing a slight decrease.

240 Spatially, lakes in sub-region NW are rising faster than that in sub-region NE, and also rising

241 trends are very significant in the northern part of the TP.

242 *3.2. Lake level and storage change*

243 Lake level changes from 2010 to 2015 were calculated as well as the corresponding storage

244 changes (Fig. 8). The rising trend in lake levels is significant. Nine (13%) lakes rose beyond 2

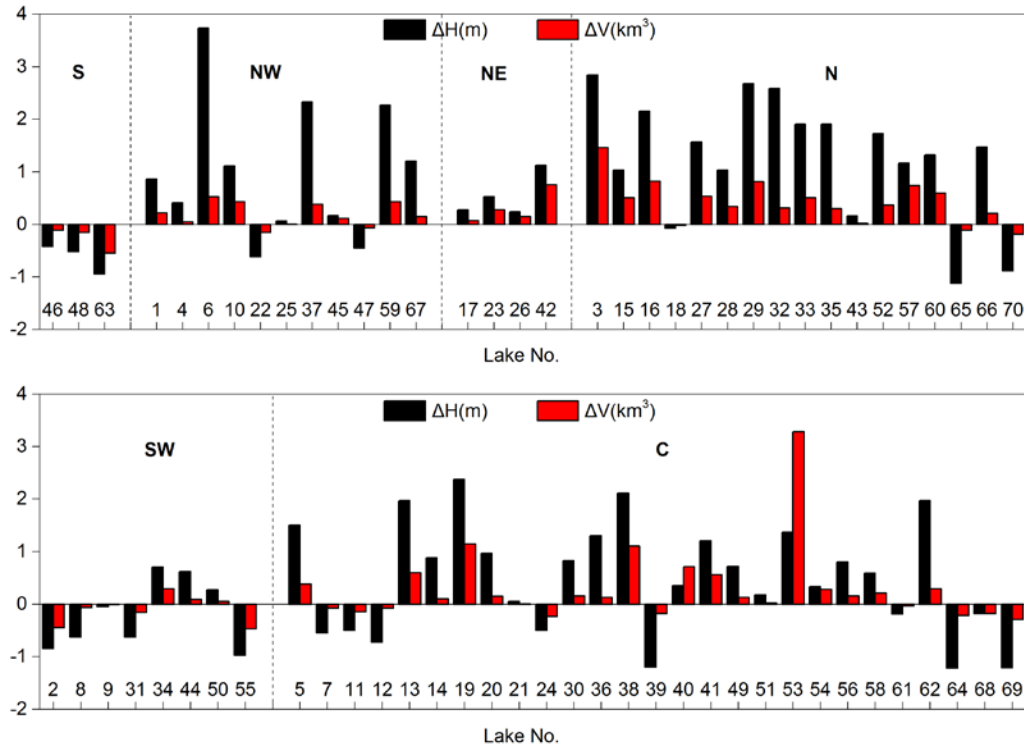
245 m, among which Bangdag Co even rose by 3.73 m. Regionally, lakes in sub-region NW and N

246 had a significant level increment with an average of 1.0 and 1.26 m, respectively.

247 Comparatively, for lakes that were declining, the magnitude of the trend is small. Only 4 lakes

248 exhibited a decline of the order of -1.2 m while the others (82%) just within 1 m. Besides, these

249 lakes were relatively small in area and thus the storage loss was limited.



250

251 Figure 8: Lake level and storage change from 2010 to 2015

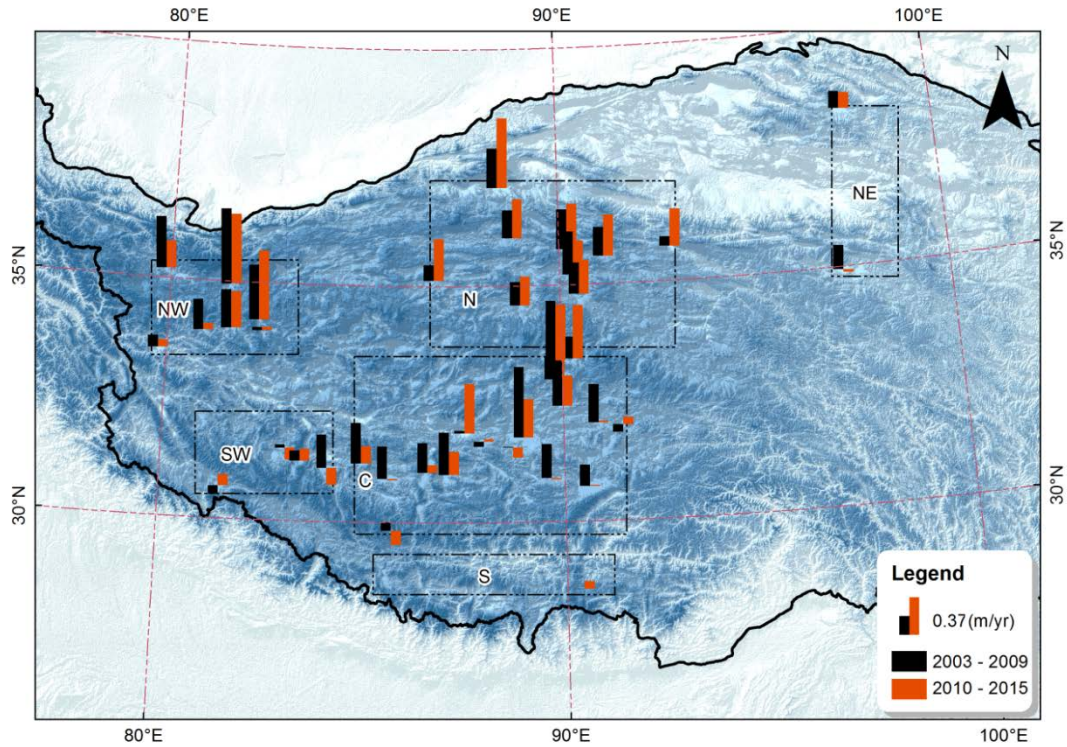
252 The increase in net water storage is estimated as $17.0 \times 10^9 \text{ m}^3$ from 2010 to 2015. Figure
 253 8 reveals that Aqqikkol (3), Dorsoidong Co (19), Migriggyangzham Co (38) and Siling Co (53)
 254 all gained more than $1 \times 10^9 \text{ m}^3$, and contributed 41.2% of total volume gained.

255 *3.3. Comparison between different periods*

256 The level variations of 42 lakes are compared during two periods, i.e., 2003-2009 and
 257 2010-2015. Figure 9 illustrated the distribution and change of 42 lakes. It is clear that almost
 258 all lakes kept rising (Fig. A1 & Fig. 9) and the mean rising rate are almost the same, i.e. 0.33
 259 and 0.32 m/yr during two periods.

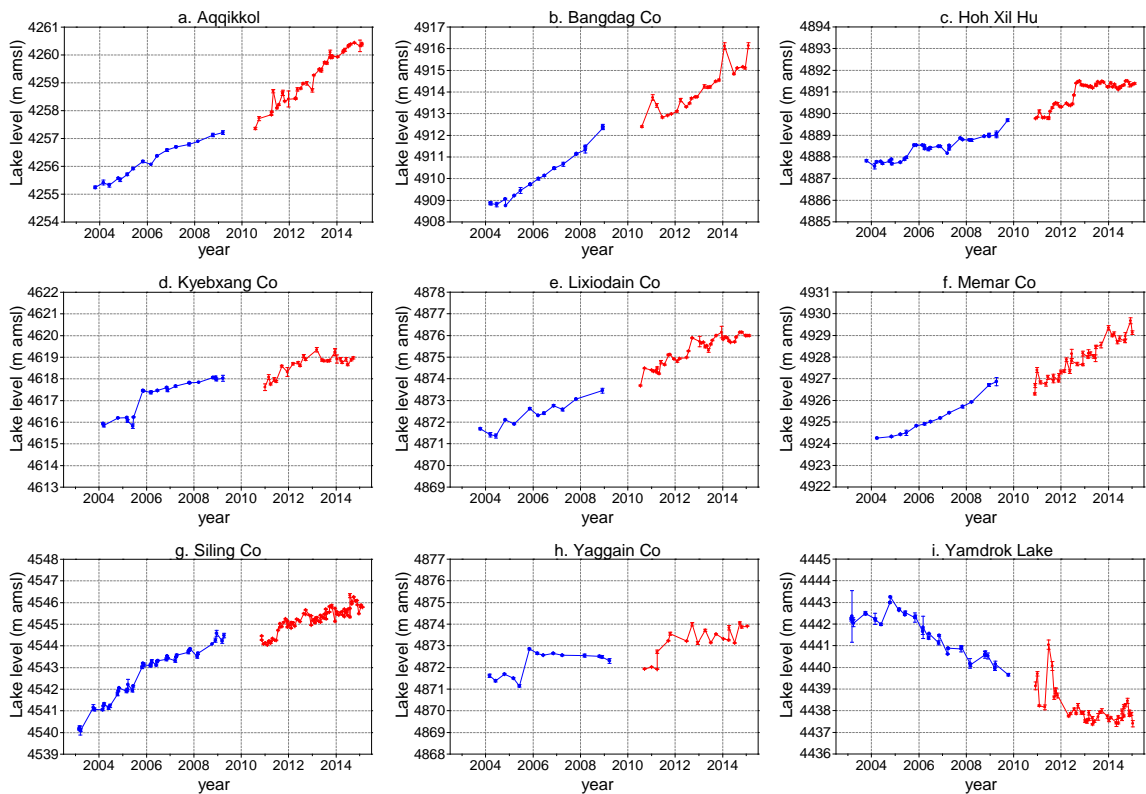
260 In sub-region NW and N, lakes maintained rising trend and the rising rates of two periods
 261 were comparable, such as Bangdag Co, Lixiodain Co, Memar Co (Fig. 10). Some lakes in sub-
 262 region N, even arose more sharply, compared to 2003-2009. For instance, Aqqikkol lake arose

263 twice as fast as it was during 2003-2009 (Fig. 10).



264

265 Figure 9: Map of lake level change rates during the periods of 2003-2009 and
266 2015



267

268 Figure 10: Evolution of lake levels for nine lakes during the period of 2003-2015
269 (ICESat time series in blue and Cryosat-2 time series in red)

270 Kyebxang Co and Yaggain Co experienced a similar rising process, i.e., an abrupt rising
271 in 2005 followed by a relatively steady stage, and in recent five years, had a ~2 m rising. Siling
272 Co, the largest lake after Qinghai Lake on the TP, kept rising during the whole period (Fig. 10).

273 Twelve of the 42 lakes changed the evolution process from increase to decrease or vice
274 versa. These lakes were mainly distributed in sub-region C and SW. Most of them are just
275 slowing the rising trend, having a steady stage or slightly decreasing (Table A1). The only one
276 kept significant declining is Yamdrok Lake which has declined 5 m during 2003-2015 (Fig. 10).

277 4. Discussion

278 Lakes on the TP are mainly affected by natural processes and most of them are closed lakes.
279 The inflows include precipitation over the lake, surface runoff derived from precipitation and
280 glacier/snow. The outflow is mainly evaporation. Thus, the lake water balance can be expressed
281 as below:

$$282 \quad \Delta H = P + R - E \pm \varepsilon, \quad (8)$$

283 where ΔH is the lake level change, P is the precipitation over the lake, R is the depth of inflow
284 derived from basin precipitation and glacier/snow meltwater, E is the evaporation over the lake,
285 and ξ is the sum of groundwater exchange and permafrost thawing recharge. All components
286 are expressed as depth for lake in units of meter.

287 To investigate the potential factors contributing to lake level change, lake basin-wide
288 climate normals and change rates of precipitation and temperature, supply coefficient, glacier
289 ratio and basin elevation were regressed against level change rate for 54 endorheic lakes (Table

290 3). In the following sub-sections, we will discuss the main potential factors in detail.

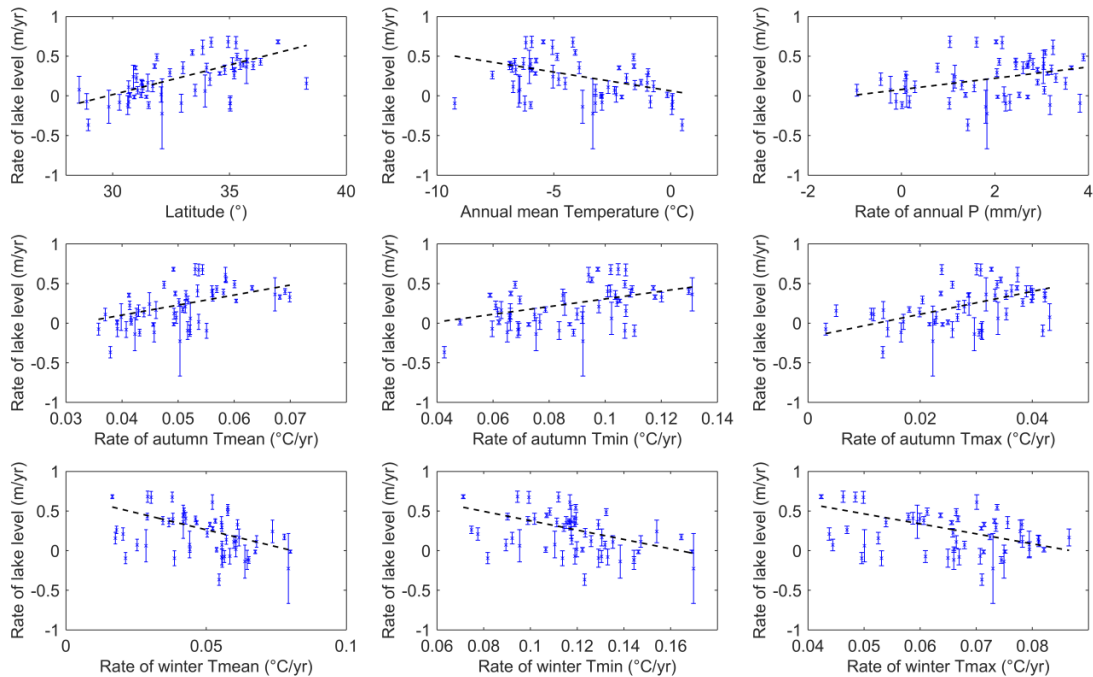
291 *4.1. Climate factors*

292 Precipitation (P) and evaporation (E) are the two most direct climatic factors affecting the
293 lake level. For example, the coherent lake growth on the TP interior was mainly attributed to
294 increased precipitation and decreased evaporation (Lei et al., 2014). Similarly, Song et al. (2015)
295 also concluded that annual lake level variations were mainly related to precipitation and
296 evaporation variability. Nevertheless, a recent case study shows that evaporation decrease just
297 accounts for about 4% of the expansion of Nam Co (Ma et al., 2016). However, evaporation is
298 closely related to temperature, wind, insolation and the duration of ice-free condition. Most of
299 the previous studies did not consider the duration of lake evaporation, and moreover, potential
300 evapotranspiration was used to calculate lake water balance instead of evaporation over lake.
301 With the rising temperature, how lake evaporation changes is still not clear. As for temperature,
302 it is indirectly influencing the lake change by melting glacier, snow and permafrost, and at the
303 meantime, it will change the evaporation over lake and evapotranspiration over the basin.

304 In our study, lake level change rate is significantly related to annual precipitation change
305 rate. Most of the lake basins show an increasing trend (Fig. 11), which results in more recharge
306 to lakes. However, the abrupt rising of six lakes in sub-region N (Fig. 5), cannot be explained
307 by increased precipitation. As we can see from Figure 5, the rise occurred over a period of about
308 2-7 months. If this was the result of increased rainfall, the precipitation amount in these months
309 should be substantial, which is not found in the data.

310 On the other hand, level change rate is significantly correlated with temperature, especially
311 autumn and winter temperature (Fig. 11). It reveals that lakes with higher change rate are

312 located in lower temperature zones where permafrost is widely distributed. This may be
 313 explained by the permafrost thawing as reported by Li et al (2014). Moreover, level change
 314 rates are significantly and positively correlated to autumn temperature change rates and summer
 315 minimum temperature, while significantly and negatively correlated to winter temperature.
 316 Autumn temperature rising speeds the thawing of permafrost, and more water may be released
 317 to recharge the lakes by means of springs and/or groundwater. However, winter temperature is
 318 below zero, and the rising just accelerates the evapotranspiration process instead of increasing
 319 meltwater.



320
 321 Figure 11: Correlation between different factors (x-axis) and lake level change rate (y-
 322 axis)

323

324 4.2. Glacier meltwater

325 Glacier meltwater is an important recharge source for lakes with glaciated headwaters, and
 326 it is widely considered as the most crucial factor attributing to lake rising (Zhang et al., 2011).

327 On the other hand, the study of Li et al.(2014) shows that glacier melt has a limited influence
328 on lake changes. For most lake basins the glacier ratio is very small and some are free of glaciers
329 (Table A1). In this study, the relationship between level change rate and glacier ratio was unclear.
330 Thus, in this study glacier meltwater is not found to be a global factor for the TP lakes even
331 though it contributes to net water balance for certain lakes.

332 *4.3. Permafrost*

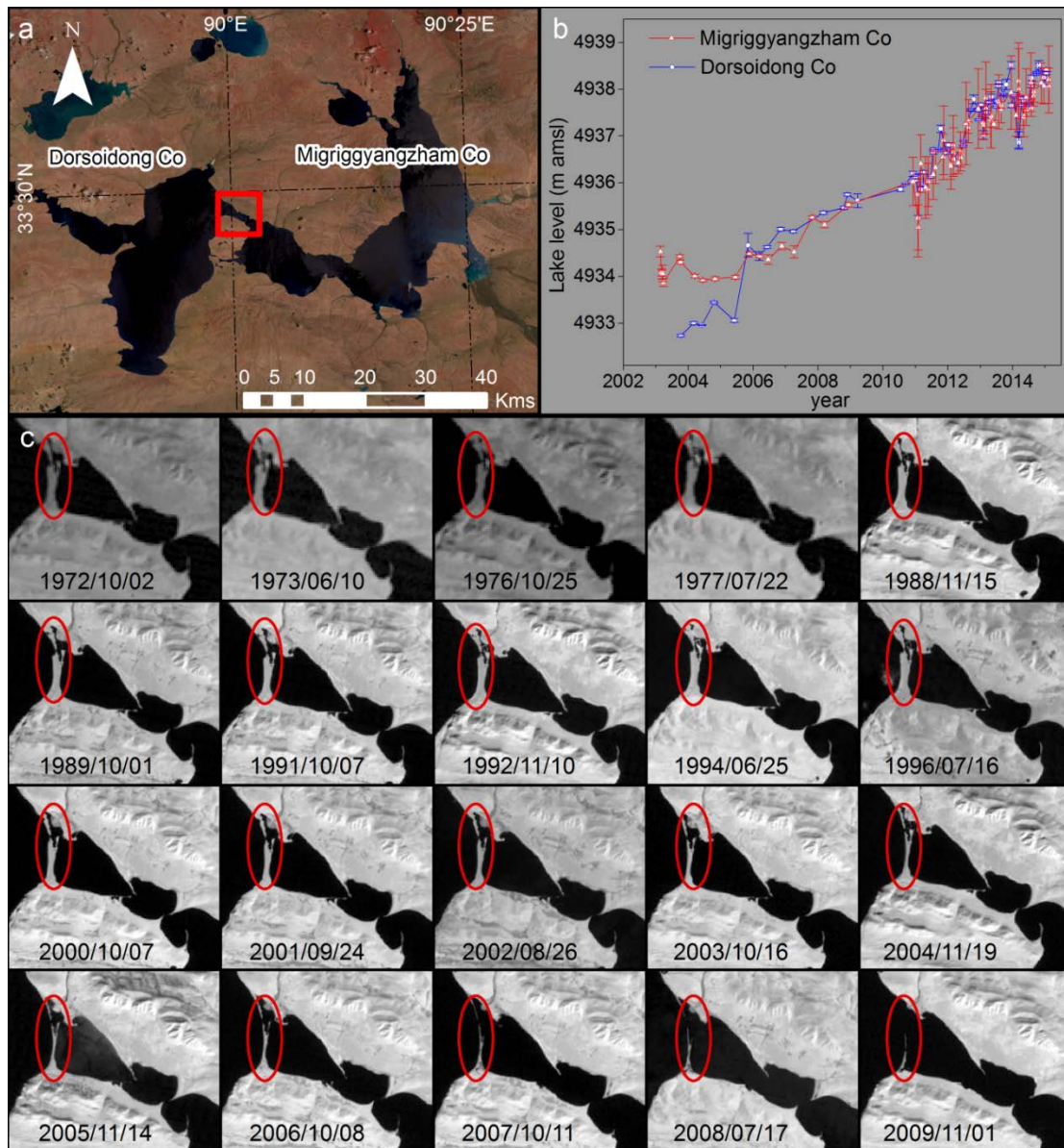
333 Warming temperature leads to the degradation of permafrost, and may even lead to a
334 breach of permafrost layer beneath lakes and thus result in exchange between lake and the
335 subsurface(Smith et al., 2005). The repeated freeze-thaw cycles create increased porosity and
336 permeability which may lead to better exchange conditions for supra-permafrost water (Cheng
337 and Jin, 2012). Recently, Johansson et al. (Johansson et al., 2015) studied the interactions
338 between lake, active layer and talik in a continuous permafrost catchment. In the northern
339 region of the TP, continuous permafrost is well developed and lakes maintained rising in the
340 past decade. Permafrost affects the lake balance, but it is still a challenge to estimate the quantity
341 of water released. However, in our regression analysis, level change rate is significantly
342 negatively correlated to temperature, which indicates that permafrost plays an important role in
343 lake rising. This may be the reason of the abrupt rising of lakes in sub-region N.

344 *4.4. Geological and geomorphological settings*

345 The geological setting determines the shape and characteristics of lakes, and it does not change
346 significantly over short-time scales. Nevertheless, the geomorphological setting can influence a lake
347 by altering the river channels and/or the lake basin area (Liu et al., 2013). In addition, adjacent lakes

348 will merge when at highstand and separate at lowstand. Another case is discharge from one to
349 another when the lake level reaches the elevation of the divide between them (Fig. A2). For example,
350 Dorsoidong Co and Migriggyangzham Co are two lakes connected after rising.

351 Dorsoidong Co and Migriggyangzham Co (also called Chibuzhang Co) are two large sister
352 lakes. Using images from 1972 to 2015, we found that they were connected in 2005 (Fig. 12).
353 Dorsoidong Co had a rapid increase during June 2005 to October 2005, when
354 Migriggyangzham Co discharged to Dorsoidong Co through the divide. The divide (indicated
355 by red circle in Fig. 12) of the pond connecting them is 4935 from SRTM DEM. Thus once the
356 level of Migriggyangzham Co first reaches 4935 m, it will recharge Dorsoidong Co. This can
357 be confirmed by the water level time series (Fig. 12). At the end of 2007, the levels of both
358 lakes reached 4935.2 m and increased in lockstep. Therefore, the rising of Dorsoidong Co since
359 2005 is partially due to the discharge of Migriggyangzham Co. This phenomenon is also
360 reported by other studies (Song and Sheng, 2016; Tseng et al., 2016).



361
 362 Figure 12: Maps of Dorsoidong Co and Migriggyangzham Co. a) lake location (red
 363 rectangle is shown in figure c; b) long-term time series; c) zoom-in view of the
 364 connection between two lakes on different dates (red ellipse indicates the pond
 365 connecting two lakes)

366

367 4.5. Groundwater exchange

368 Generally, groundwater exchange is not considered in a lake balance study. The reason is
 369 twofold, one: the fine lake sediment and permafrost serve as impermeable layers and two: no
 370 data are available (Song et al., 2015a). However, some studies revealed that groundwater

371 exchange plays an important role which cannot be neglected. For example, Zhou et al. (2013)
372 found that the inflow do not balance outflow if lake discharge is not considered, and inflow is
373 more than outflow by 810-1220 mm one year.

374 In the southern region of the TP, permafrost zone is discontinuous and with limited areal
375 extent and thickness (Cheng and Jin, 2012). The groundwater is closely linked to rivers and
376 lakes. Andermann et al. (2012) found that groundwater contributes more than ice and snow in
377 central Himalaya.

378 Groundwater discharge in the form of depression springs occurs widely in the northern
379 part of the TP according to Wang and Dou (1998) and the first author encountered many hot
380 springs during field work in 2012 and 2013.

381 Under climate change, glacier and permafrost respond heterogeneously. Considering the
382 heterogeneity of topography and diversity of supply sources, different factors contribute to
383 lakes change. Therefore, it is not possible to draw a conclusion at the TP scale.

384 **5. Conclusion**

385 In our study, 70 large lakes ($> 100 \text{ km}^2$) were investigated. We find that 68.6% of the lakes
386 experienced a rising in lake level. These lakes were mainly clustered in northwest and northern
387 parts as well as scattered in the central part of the TP. It should be noted that 88% of the lakes
388 in sub-region N (Northern part of the TP), were expanding drastically with an average rate of
389 0.374 m/yr. Nevertheless, of the 31.4% declining lakes, only 7 showed a decreasing rate greater
390 than 0.1 m/yr. In conclusion, rising was the dominant changing trend of these lakes. The
391 estimation of water storage change in these lakes is $17.6 \times 10^9 \text{ m}^3$ from 2010 to 2015, 41.2% of

392 which is contributed by Aqqikkol, Dorsoidong Co, Migriggyangzham Co and Siling Co.

393 Furthermore, compared with the change rates during 2003-2009, 28 of the 42 lakes
394 maintained rising trend and their rates are comparable. Lakes in sub-region N and NW show a
395 consistent rising with an average of about 5 m in the period of 2003-2015 although several lakes
396 in sub-region N were steady in recent years.

397 By factor analysis, we discover that the temperature is closely related to lake level change
398 rate and autumn and winter temperatures play opposite roles. Besides, the latitude is
399 significantly related to level change rate. This new result may indicate that freeze-thaw
400 processes of permafrost are driving forces behind observed lake change. More research is
401 needed on the influence of permafrost. No coherent process exists for all lakes and the rising
402 mechanism cannot be explained by one single factor.

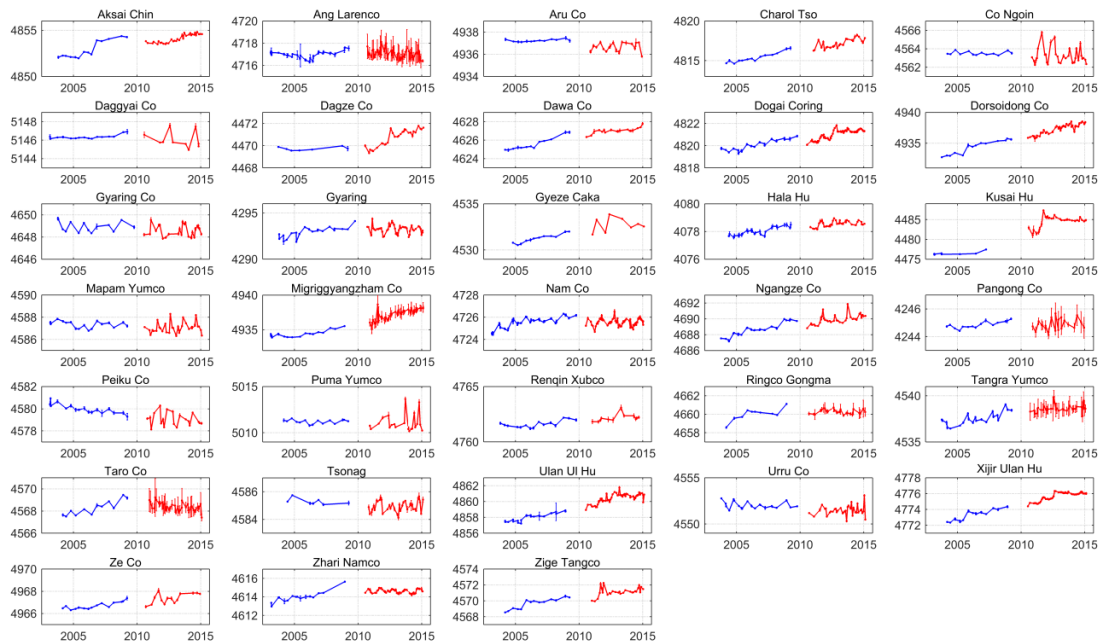
403 In addition, compared to ICESat altimetry data, Cryosat-2 covers more lakes due to its
404 dense distribution of ground tracks. The upcoming SAR altimetry missions (e.g. Sentinel-3 with
405 a cycle period of 27 days) will be of value in monitoring lake level changes.

406 **Acknowledgements**

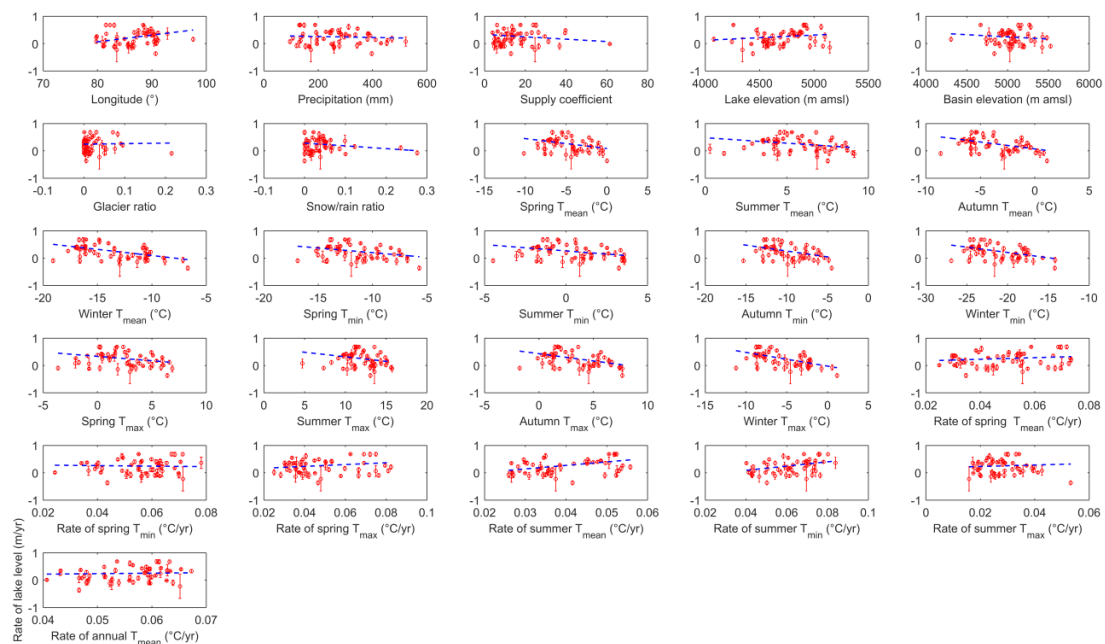
407 We thank the China Meteorological Administration, the European Space Agency (ESA) for
408 providing meteorological data and CryoSat-2 data, respectively. Provision of ICESat lake level
409 data by University of Bristol is also acknowledged. The first author thanks the funding support
410 from China Scholarship Council.

411 **Appendix**

412 The details of lake number, name, location, change rates of different periods, etc. are listed in
 413 Table A1 shows the correlation between other 26 factors and lake level change rate. Figure A2
 414 illustrates the evolution of level during 2003 – 2015 for other 33 lakes. Cases of lakes with
 415 potential recharge relationship are shown in Figure A3.

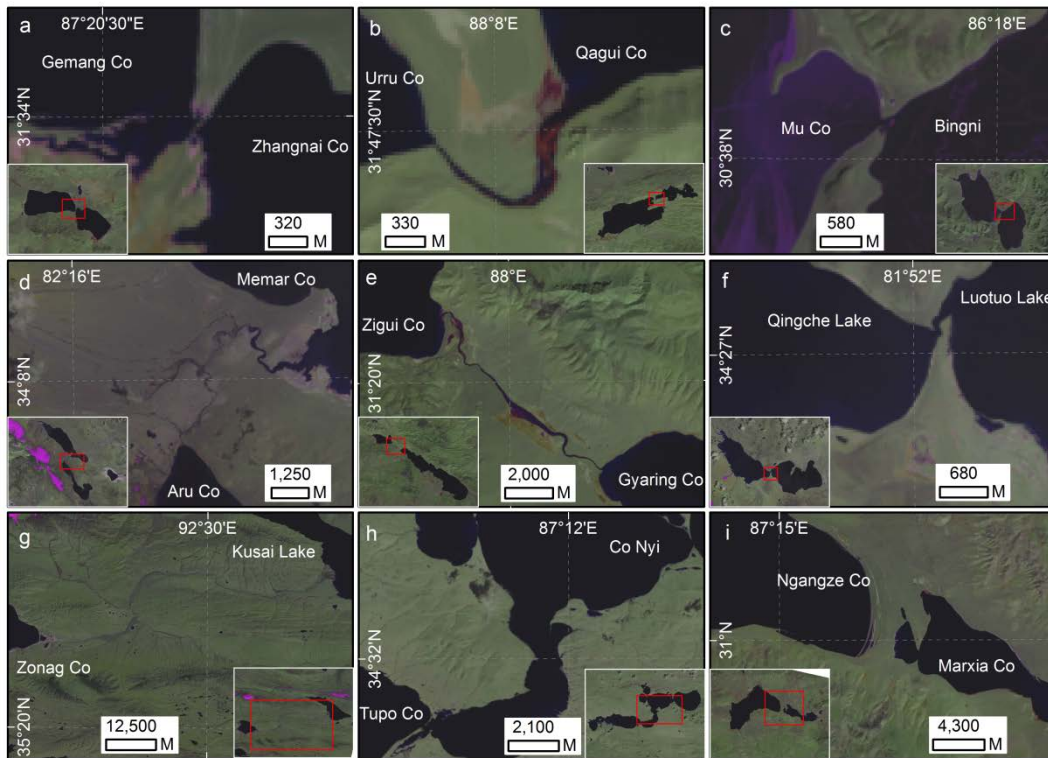


416
 417 **Figure A1: Correlation between other 26 factors and lake level change rate (appendix**
 418 **to Fig. 8)**



419

420 Figure A2: Evolution of lake levels during the period of 2003-2015 for other 33 lakes
 421 (ICESat time series in blue and Cryosat-2 time series in red) (appendix to Fig. 10)



422
 423 Figure A3: Cases of lakes with potential recharge relationship

424

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